CHAPTER 1

INTRODUCTION

1-1. Purpose and Scope.

a. This manual provides general information, design criteria and procedures, static and dynamic analysis procedures, temperature studies, concrete testing requirements, foundation investigation requirements, and instrumentation and construction information for the design of concrete arch dams. The guidance provided in this manual is based on state of the art in this field as practiced at the time of publication. This manual will be updated as changes in design and analysis of arch dams are developed. The information on design and analysis presented in this manual is only applicable to arch dams whose horizontal and vertical sections are bounded by one or more circular arcs or a combination of straight lines and circular arcs.

b. This manual is a product of the Arch Dam Task Group which is a component of the Computer-Aided Structural Engineering (CASE) Program of the U.S. Army Corps of Engineers (USACE). Task group members are from the USACE, U.S. Bureau of Reclamation (USBR), and the Federal Energy Regulatory Commission (FERC). Individual members and others contributing to this manual are as follows: Donald R. Dressler (CECW-ED), Jerry L. Foster (CECW-ED), G. Ray Navidi (CEORH-ED), Terry W. West (FERC), William K. Wigner (CESAJ-EN), H. Wayne Jones (CEWES-IM), Byron J. Foster (CESAD-EN), David A. Dollar (USBR), Larry K. Nuss (USBR), Howard L. Boggs (USBR, retired/consultant), Dr. Yusof Ghanaat (QUEST Structures/consultant) and Dr. James W. Erwin (USACE, retired/consultant).

c. Credit is given to Mr. Merlin D. Copen (USBR, retired) who inspired much of the work contained in this manual. Mr. Copen's work as a consultant to the U.S. Army Engineer District, Jacksonville, on the Corps' first double-curved arch dam design, Portugues Arch Dam, gave birth to this manual. Professor Ray W. Clough, Sc. D. (Structures consultant), also a consultant to the Jacksonville District for the design of the Portugues Arch Dam, provided invaluable comments and recommendations in his review and editing of this manual.

1-2. Applicability.

This manual is applicable to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having civil works responsibilities.

1-3. References and Related Material.

a. References. References are listed in Appendix A.

b. Related Material. In conjunction with this manual and as part of the Civil Works Guidance Update Program, a number of design and analysis tools have been developed or enhanced for use by USACE districts. A brief description is as follows:

(1) Arch Dam Stress Analysis System (ADSAS) (U.S. Bureau of Reclamation (USBR) 1975). This is the computerized version of the trial load method of analyzing arch dams developed by the Bureau of Reclamation. ADSAS has been converted from mainframe to PC and a revised, user-friendly manual has been prepared. ADSAS is a powerful design tool which has been used in the design of most modern arch dams in the United States.

(2) Graphics-Based Dam Analysis Program (GDAP) (Ghanaat 1993a). GDAP is a finite element program for static and dynamic analysis of concrete arch dams based on the Arch Dam Analysis Program (ADAP) that was developed by the University of California for the USBR in 1974. The GDAP program is PC-based and has graphics pre- and postprocessing capabilities. The finite element meshes of the dam, foundation rock, and the reservoir are generated automatically from a limited amount of data. Other general-purpose finite element method (FEM) programs can also be used for the analysis of arch dams.

(3) Interactive Graphics Layout of Arch Dams (IGLAD) is an interactive PC-based program for the layout of double-curvature arch dams. The program enables the designer to prepare a layout, perform necessary adjustments, perform stress analyses using ADSAS, and generate postprocessing graphics and data. This program was developed by the USACE.

1-4. Definitions. Terminology used in the design and analysis of arch dams is not universal in meaning. To avoid ambiguity, descriptions are defined and shown pictorially, and these definitions will be used throughout this manual.

a. Arch (Arch Unit). Arch (or arch unit) refers to a portion of the dam bounded by two horizontal planes, 1 foot apart. Arches may have uniform thickness or may be designed so that their thickness increases gradually on both sides of the reference plane (variable thickness arches).

b. Cantilever (Cantilever Unit). Cantilever (or cantilever unit) is a portion of the dam contained between two vertical radial planes, 1 foot apart.

c. Extrados and Intrados. The terminology most commonly used in referring to the upstream and downstream faces of an arch dam is extrados and intrados. Extrados is the upstream face of arches and intrados is the downstream face of the arches. These terms are used only for the horizontal (arch) units; the faces of the cantilever units are referred to as upstream and downstream, as appropriate. See Figure 1-1 for these definitions.

d. Site Shape. The overall shape of the site is classified as a narrow-V, wide-V, narrow-U, or wide-U as shown in Figure 1-2. These terms, while being subjective, present the designer a visualization of a site form from which to conceptually formulate the design. The terms also help the designer to develop knowledge and/or experience with dams at other sites. Common to all arch dam sites is the crest length-to-height ratio, cl:h. Assuming for comparison that factors such as central angle and height of dam are equal, the arches of dams designed for wider canyons would be more flexible in relation to cantilever stiffness than those of dams in narrow canyons, and a proportionately larger part of the load would be carried by cantilever action.

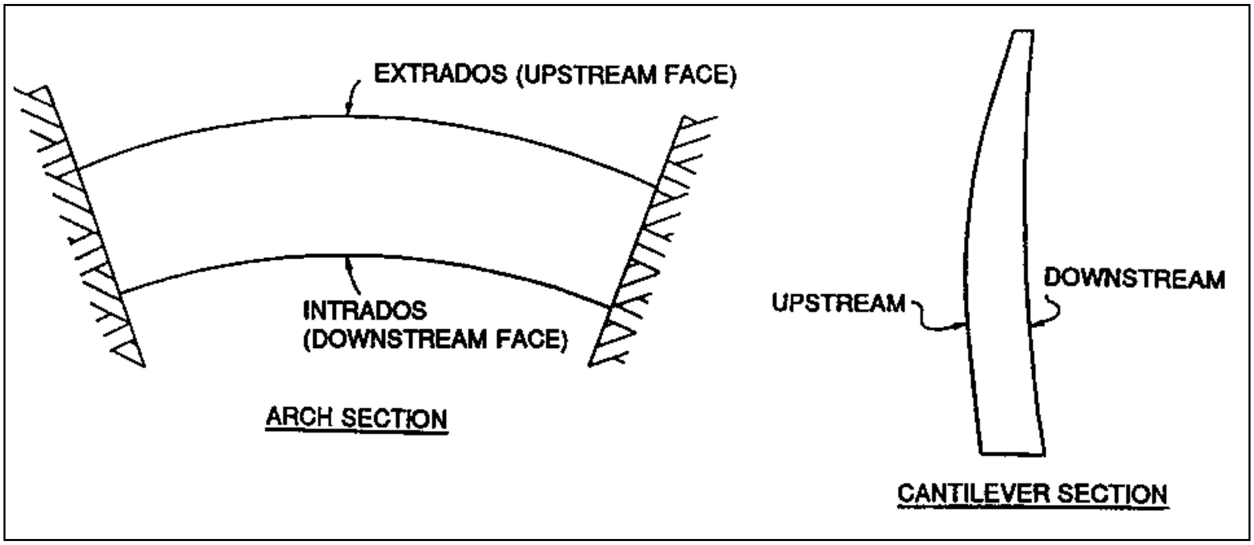

Figure 1-1. Typical arch unit and cantilever unit

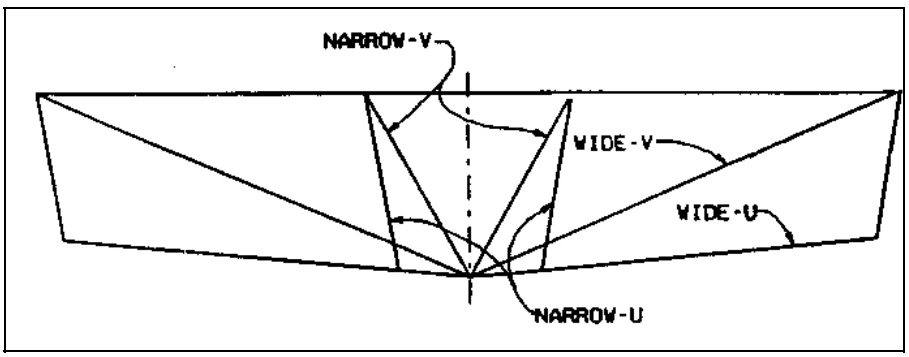

Figure 1-2. Schematic profiles of various dam sites

e. Crest Length-Height Ratio. The crest length-to-height ratios of dams may be used as a basis for comparison of proposed designs with existing conditions and with the relative effects of other controlling factors such as central angle, shape of profile, and type of layout. The length-to-height ratio also gives a rough indication of the economic limit of an arch dam as compared with a dam of gravity design (Figure 1-2). See paragraph 2-1b for general guidelines.

f. Narrow-V. A narrow-V site would have a cl:h of 2:1 or less. Such canyon walls are generally straight, with few undulations, and converge to a narrow streambed. This type of site is preferable for arch dams since the applied load will be transferred to the rock predominantly by arch action. Arches will be generally uniform in thickness, and the cantilevers will be nearly vertical with some slight curvature at the arch crown. Faces most likely will be circular in plan, and the dam will be relatively thin. From the standpoint of avoiding excessive tensile stresses in the arch, a type of layout should be used which will provide as much curvature as possible in the arches. In some sites, it may be necessary to use variable-thickness arches with a variation in location of circular arc centers to produce greater curvature in the lower arches. Figure 1-4 shows an example of a two-centered variable-thickness arch dam for a nonsymmetrical site.

g. Wide-V. A wide-V site would have a cl:h of 5:1 or more. The upper limit for cl:h for arch dams is about 10:1. Canyon walls will have more pronounced undulations but will be generally straight after excavation, converging to a less pronounced v-notch below the streambed. Most of the live load will be transferred to rock by arch action. Arches will generally be uniform in thickness with some possible increase in thickness near the abutments. The "crown" (central) cantilever will have more curvature and base thickness than that in a narrow-V of the same height. In plan, the crest most likely would be three-centered and would transition to single-center circular arches at the streambed. Arches would be thicker than those in the narrow-V site.

h. Narrow-U. In narrow-U sites, the canyon walls are near vertical in the upper half of the canyon. The streambed width is fairly large, i.e., perhaps one-half the canyon width at the crest. Above 0.25h, most of the live load will be transferred to rock by arch action. Below 0.25h, the live load will increasingly be supported by cantilever action toward the lowest point. There the cantilevers have become stubby while the arches are still relatively long. The upper arches will be uniform in thickness but become variable in thickness near the streambed. The crown cantilever will have more curvature than the crown cantilever in a narrow-V site of equal height. Faces will generally be circular in plan. Arches will be thin because of the narrow site. In dams constructed in U-shaped canyons, the lower arches have chord lengths almost as long as those near the top. In such cases, use of a variable-thickness arch layout will normally give a relatively uniform stress distribution. Undercutting on the upstream face may be desirable to eliminate areas of tensile stress at the bases of cantilevers.

i. Wide-U. Wide-U sites are the most difficult for an arch dam design because most of the arches are long compared to the crest length. In the lower 0.25h, much of the live load is carried by cantilever action because the long flexible arches carry relatively little load. In this area, cantilever thickness tends to increase rapidly to support the increased water pressure. Arch thickness variation in the horizontal direction may range from uniform at the crest to variable at the streambed. The transition will most likely occur at about the upper one-third level. The crown cantilever here should have the most curvature of any type of site.

j. Reference Plane. As shown in Figures 1-3 through 1-5, the reference plane is a vertical radial plane usually based in the streambed. The reference plane contains the crown cantilever and the loci of the central centers as shown in Figure 1-6. It is from this plane that the angle to the arch abutment is measured. Also shown are the axis and axis center. The axis is a vertical surface curved in plan intersecting the crown cantilever at the crest and upstream face. The axis is developed in plan by the axis radius which is the distance between the axis and the axis center located downstream. A method of estimating values for these terms will be described in a later section. The reference plane will theoretically consist of one, two, or three planes of centers. One plane of centers is used to describe arches in a symmetrical site as shown in Figure 1-3. Two planes of centers are used to describe arches in nonsymmetrical sites as shown in Figure 1-4. Three planes

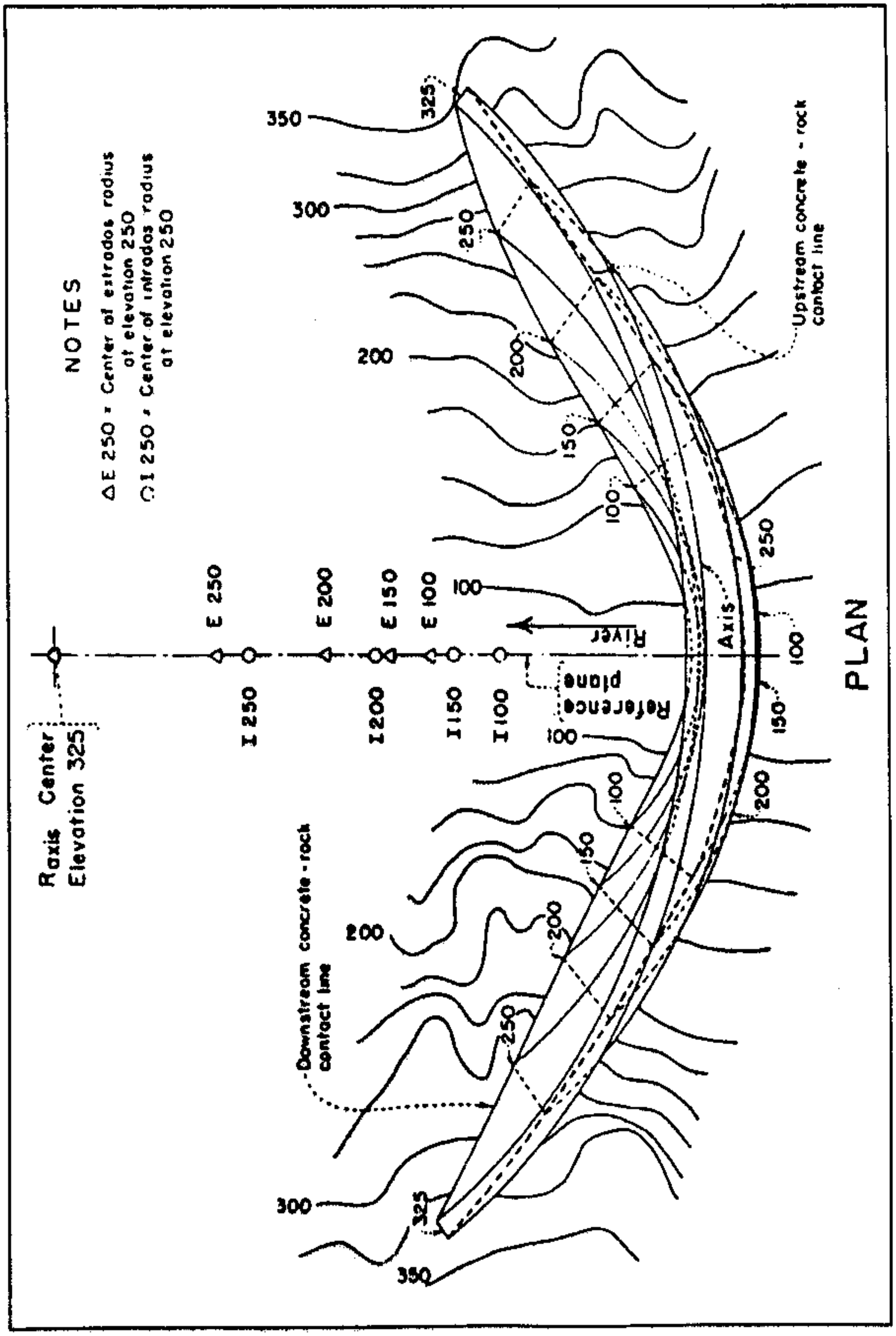

Figure 1-3. Typical single-center variable thickness arch dam in a symmetrical site

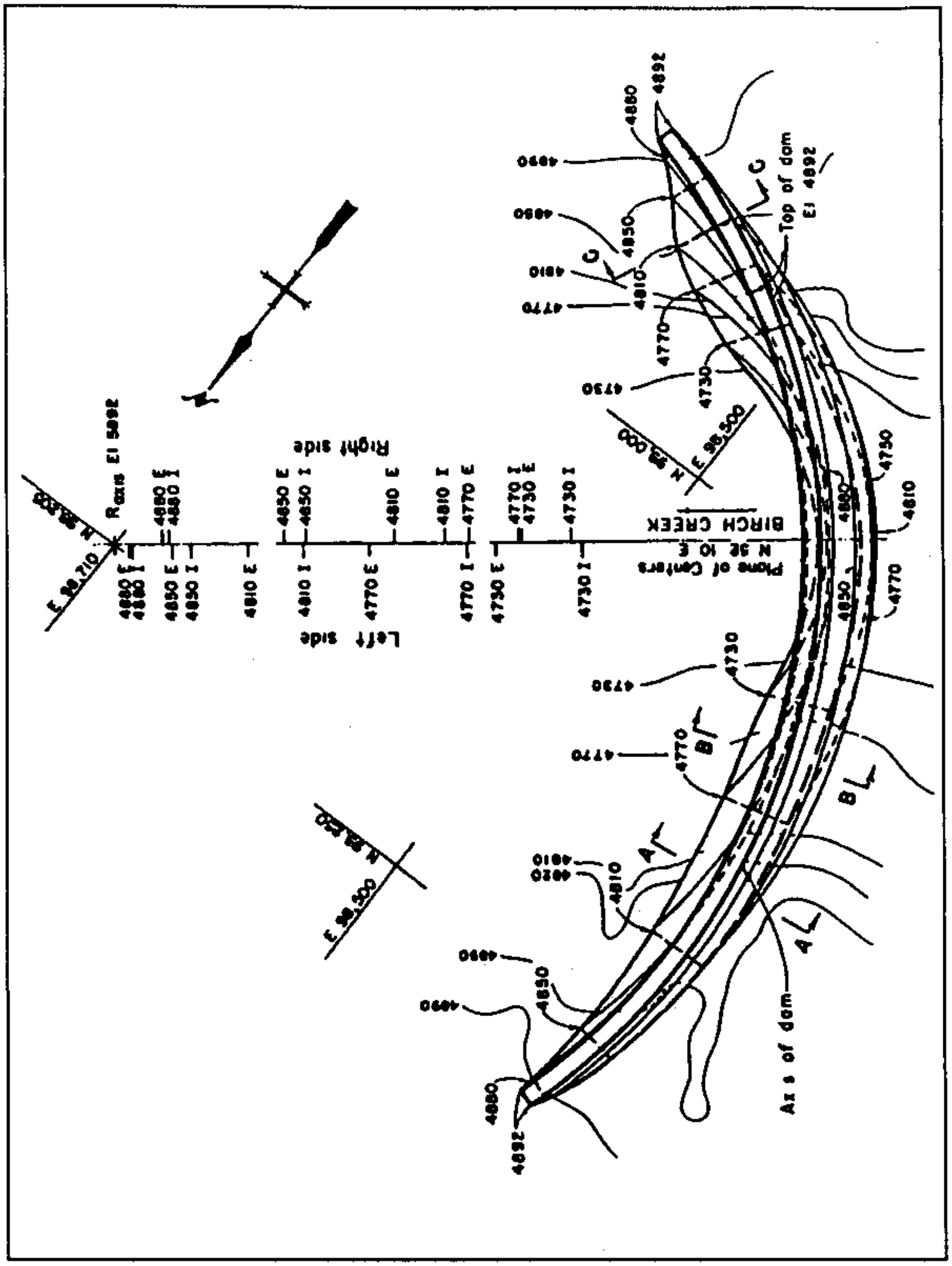

Figure 1-4. Typical two-centered variable-thickness arch dam in a nonsymmetrical site

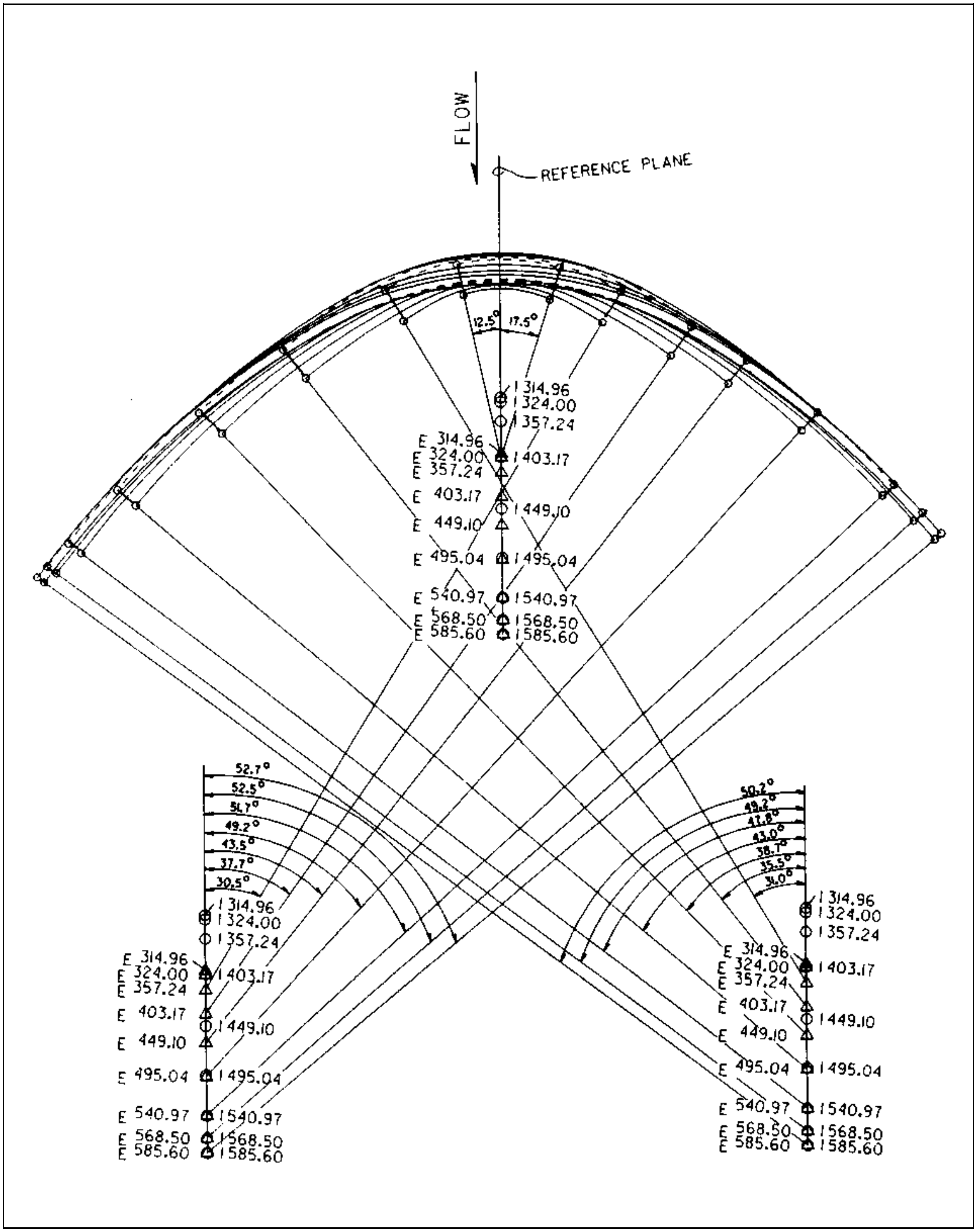

Figure 1-5. Plan of a three-centered variable-thickness arch dam

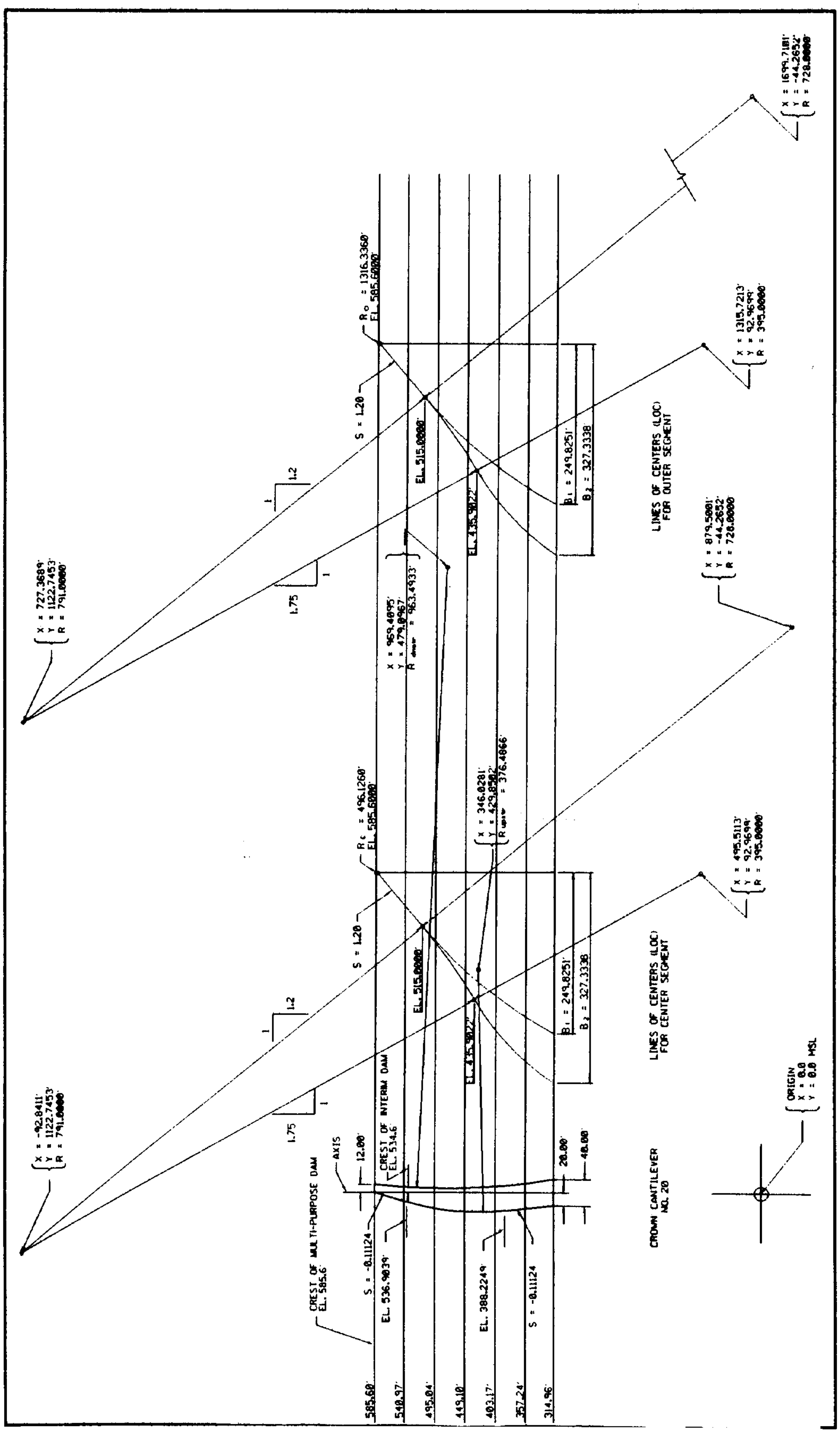

Figure 1-6. Section along reference plane of plane shown in Figure 1-5

of centers are used to describe a three-centered arch dam as shown in Figure 1-5.

k. Crown Cantilever. The crown cantilever is defined as the maximum height vertical cantilever and is usually located in the streambed. It is directed radially toward the axis center. The crown cantilever and the arch crowns are at the same location on symmetrical arch dams. On nonsymmetrical arch dams, the arch crowns will be offset toward the longer side. Maximum radial deflections will occur at the crown cantilever of symmetrical dams but generally between the crown cantilever and arch crowns on nonsymmetrical arch dams.

l. Single Curvature. Single-curvature arch dams are curved in plan only. Vertical sections, or cantilevers, have vertical or straight sloped faces, or may also be curved with the limitation that no concrete overhangs the concrete below. These types of shapes were common prior to 1950.

m. Double Curvature. Double-curvature arch dams means the dam is curved in plan and elevation as shown in Figure 1-7. This type of dam utilizes the concrete weight to greater advantage than single-curvature arch dams. Consequently, less concrete is needed resulting in a thinner, more efficient dam.

n. Overhang. Overhang refers to the concrete on the downstream face where the upper portion overhangs the lower portion. Overhang is most at the crown cantilever, gradually diminishing toward the abutments. The overhanging concrete tends to negate tension on the downstream face in the upper one-quarter caused by reaction of the lightly loaded upper arches.

o. Undercutting. Undercutting refers to the upstream face where the concrete/rock contact undercuts the concrete above it. Undercutting causes the moment from concrete weight to compress the concrete along the heel and tends to negate tension from the reservoir pressure. If an exaggerated undercutting becomes necessary, an imbalance during construction may occur in which case several of the concrete blocks may have to be supported with mass concrete props placed integrally with the blocks. Each prop width is less than the block width to avoid additional arch action. The lowest lift within the prop is painted with a bond breaker to avoid additional cantilever action. Undercutting is most predominant at the base of the crown cantilever. Generally, as the crest length-to-height ratio increases so do the overhang and the undercutting.

p. Symmetrical. In addition to the canyon shapes previously described, the canyon is also described as symmetrical or nonsymmetrical. In general, sites are not absolutely symmetrical but are considered symmetrical if the arch lengths on each side differ by less than about 5 percent between 0.15H and 0.85H. Figure 1-3 shows the plan view of a typical dam in a symmetrical site.

q. Nonsymmetrical. Nonsymmetrical sites result in dams with longer arches on one side of the crown cantilever than the other. Dams for such sites will quite possibly have two reference planes, one for each side but with a common crown cantilever as shown in Figure 1-4. The short side with

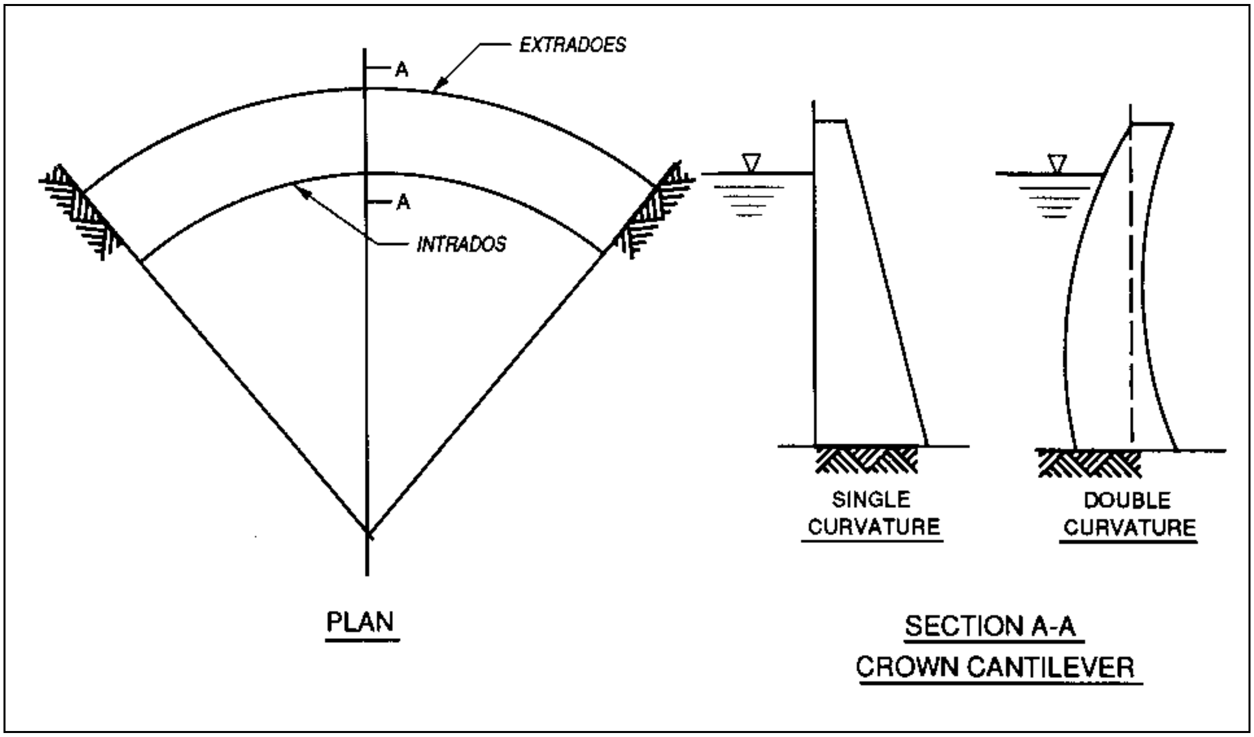

Figure 1-7. Example of single- and double-curvature dams

the steeper-wall canyon will have shorter radii and exhibit more arch action. Whereas the longer side, abutting into the flatter slope, will have less arch action and will be relatively thicker along the abutments. In general, the maximum deflection at each elevation will not occur at the crown cantilever but more toward the midpoint of each arch. A different axis radius for each side will be necessary. To maintain continuity, however, each pair of lines must lie along the reference plane. In some cases the axis radius (R_{axis}) may be different on each side, and the arches may be uniform or variable in thickness. A region of stress concentration is likely to exist in an arch dam having a nonsymmetrical profile. In some cases improvements of a nonsymmetrical layout by one or a combination of the following methods may be warranted: by excavating deeper in appropriate places, by constructing an artificial abutment, or by reorienting and/or relocating the dam.

r. Lines of Centers. A line in space which is the loci of centers for circular arcs is used to describe a face of the dam. For uniform-thickness arches, a single line of centers will describe the extrados and intrados faces. Variable-thickness arches require two lines of centers. Nonsymmetrical sites need one or two lines of centers for each side of the dam. Three-centered arches have three lines of centers as shown in Figure 1-6. It should be noted in Figure 1-6 that the lines of centers for the outer segments are identical and only one pair is shown. Also, in Figure 1-6, arches of variable thickness are used below elevation 515 feet.

s. Constant Center. A constant-center dam has a vertical line at the axis center to describe the center for all arches. All arches are uniform in thickness and the crown cantilever is representative of all vertical sections.

t. Single Center. Single-center constant thickness arches have the same center describing the extrados and the intrados which means all arches are uniform in thickness between abutments. Single-center variable-thickness arches have different centers describing the extrados and the intrados; however, both lie along the reference plane. The lines of centers need not be vertical but must be coplanar with the crown cantilever. This arch shape is applicable to narrow canyon sites such as those with cl:h less than 3:1.

u. Two Centered. In two-centered arches, both planes are coplanar with the crown cantilever. The left plane contains the extrados and intrados lines of centers required to properly shape the left side of the arches as measured from the crown cantilever to the abutments. The right plane of centers contains the extrados and intrados lines of centers for the right-side arches.

v. Three Centered. With three-centered arches, only the center segment is coplanar with the crown cantilever. The center segment and outer segment are coplanar at an angle of compound curvature as measured from the reference plane. Three-centered arches approximate an ellipse. Figure 1-5 shows a typical three-centered arch. A parabola can be approximated by using straight tangents in the outer segment instead of arcs. Three-centered or elliptical arches can be used advantageously in wide-U or V-shaped canyons. Elliptical arches have the inherent characteristics of conforming more nearly to the line of thrust for wide sites than do circular arches. Consequently, the concrete is stressed more uniformly throughout its thickness. Because of the smaller influences from moments, elliptical arches require little, if any, variable thickness.